

# User Guide to the CIS measurements in the Cluster Active Archive (CAA)

prepared by

I. Dandouras, A. Barthe

and the CIS Team

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## 1 Introduction

The CIS (Cluster Ion Spectrometry) experiment is a comprehensive ionic plasma spectrometry package onboard the Cluster spacecraft, capable of obtaining full three-dimensional ion distributions (about 0 to 40 keV/e) with a time resolution of one spacecraft spin (4 sec) and with mass-per-charge composition determination (Rème et al., 2001).

The Cluster Active Archive (CAA) aims at preserving all measurements from the four Cluster spacecraft, so that they are usable in the long-term by the world-wide scientific community as well as by the instrument team PIs and Co-Is. This implies that the instrument data, properly calibrated, are filed together with the descriptive and documentary elements making it possible to select and interpret them (Perry et al., 2006).

This user guide is to provide help to the CAA user in using the CIS observations. All CIS datasets available in the CAA are listed in Appendix A.

## 2 Instrument Description

The CIS package consists of two different instruments:

- a time-of-flight ion *Composition and Distribution Function* analyser (CODIF, or CIS-1),
- a *Hot Ion Analyser* (HIA, or CIS-2).

In addition, each of the instruments, in order to be able to cover a dynamic range of about 6 orders of magnitude in particle fluxes, provides two different geometric factors: a *high-sensitivity side* (or HS) and a *low-sensitivity side* (or LS).

### 2.1 The CODIF (CIS-1) Instrument

The CODIF instrument combines ion energy per charge selection, by deflection in a rotationally symmetric toroidal electrostatic analyser, with a subsequent time-of-flight analysis after post-acceleration to  $\sim 15$  keV/e. Ions are selected as a function of their  $E/q$  (energy per charge) ratio, by sweeping the high voltage applied between the two toroidal hemispheres. The full energy sweep with 31 contiguous energy channels is performed 32 times per spin, and provides an energy range between about 25 eV/e and 40 keV/e. In the time-of-flight (TOF) section the velocity of the incoming ions is measured, which allows then the calculation of their  $m/q$  (mass per charge) ratio. Microchannel plate (MCP) electron

multipliers are used to detect both the ions and the secondary electrons, which are emitted from a carbon foil at the entry of the TOF section, during the passage of the ions. These secondary electrons give the “start” signal, for the time-of-flight measurement, and the position information (elevation angle of the incoming ion, provided by the MCP sectoring in anodes), cf. Fig. 2.1.

In order to cover ion populations ranging from dense magnetosheath to tenuous tail lobe, a dynamic range of more than  $10^5$  is required. CODIF therefore consists of two sections, each with a  $180^\circ$  field of view, with geometry factors differing by a factor of  $\sim 100$ : two different entrance grids are used (one per section), to reduce the incoming flux. This way, one of the sections will have counting rates which are statistically meaningful and which at the same time can be handled by the time-of-flight electronics. However, intense ion fluxes can in some cases saturate the CODIF instrument (particularly if data are acquired from the high sensitivity side), but these fluxes are measured with HIA, which is less sensitive to saturation. The operation of the high-sensitivity side (“high-G”, or “HS”) and of the low-sensitivity side (“low-g”, or “LS”) on CODIF is mutually exclusive, and only one of the two sides can be selected at a time to supply data. The field of view of the CODIF anodes is shown in Figure 2.2. With an additional Retarding Potential Analyser (RPA) device in the aperture system of the CODIF sensor, and with pre-acceleration for the energies below 25 eV/e, the range is extended to energies as low as the spacecraft potential. The retarding potential analyser operates only in the RPA mode, and provides an energy range between about 0.7 and 25 eV/e (with respect to the spacecraft potential).

## **2.2 The HIA (CIS-2) Instrument**

The HIA instrument is an ion energy-spectrometer, capable of obtaining full three-dimensional ion distributions with good angular and time resolution (one spacecraft spin). HIA combines the selection of incoming ions, according to the ion energy per charge by electrostatic deflection in a quadrispherical analyser, with a fast imaging particle detection system. This particle imaging is based on microchannel plate (MCP) electron multipliers and position encoding discrete anodes. As for CODIF, ions are selected as a function of their  $E/q$  (energy per charge) ratio, by sweeping the high voltage applied between the two hemispheres, cf. Fig. 2.3. However, with no TOF section, the ion mass cannot be resolved by HIA. The instrument has 62 energy channels but this is then reduced on-board to a lower number (mode dependent), by binning together adjacent channels, to fit into the allocated telemetry.

In order to cover populations ranging from solar wind and magnetosheath ions to tail lobe ions, a dynamic range of more than  $10^5$  is required. HIA therefore consists of two  $180^\circ$  field-of-view sections, with two different sensitivities (with a  $\sim 20$  ratio), corresponding respectively to the high-sensitivity (“high-G”, or “HS”) and to the low-sensitivity (“low-g”, or “LS”) side. The “low g” side allows detection of the solar wind and the required high angular resolution is achieved through the use of 8 sectors (or MCP anodes) around the spin plane,  $5.625^\circ$  each, the remaining 8 sectors having an  $11.25^\circ$  resolution. The  $180^\circ$  “high G” side is divided into 16 sectors,  $11.25^\circ$  each. For each sensitivity side a full  $4\pi$  steradian scan, consisting of 32 energy sweeps, is completed every spin of the spacecraft, i.e. every  $\sim 4$  s, giving a full three-dimensional distribution of ions in the energy range  $\sim 5$  eV/e - 32 keV/e. The field of view of the HIA anodes is shown in Figure 2.4.

HIA and CODIF are thus complementary instruments: ion composition and coverage of the high-energies (32-40 keV/e) are provided only by CODIF, whereas HIA provides a higher angular and energy resolution. HIA is also less prone to saturation: it does not saturate in the LS side, but the HS side can occasionally saturate. In section 6 a table is provided to help the user select the most suitable instrument, depending on the region and the ion population analysed.

## 3 Instrument Operations

### 3.1 The CIS Operational Modes

The CIS instruments have a large amount of flexibility either in the selection of the operational mode or in the reduction of the data necessary to fit the available telemetry bandwidth. CIS can thus operate in any combination of the 6 Spacecraft Telemetry Modes (3 Normal Telemetry Modes, NM1-NM3, and 3 Burst Telemetry Modes, BM1-BM3) and the 16 CIS Operational Modes.

CIS Mode		Mode Name
0	SW-1	Solar Wind / SW tracking - Mode 1
1	SW-2	Solar Wind / 3D upstreaming ions - Mode 2
2	SW-3	Solar Wind / SW tracking - Mode 3

3	SW-4	Solar Wind / 3D upstreaming ions - Mode 4
4	SW-C1	Solar Wind / SW tracking - Data Compression - Mode 1
5	SW-C2	Solar Wind / 3D upstreaming ions - Data Compression-Mode 2
6	RPA	RPA Mode
7	PROM	PROM Operation
8	MAG-1	Magnetosphere - Mode 1
9	MAG-2	Magnetosphere - Mode 2
10	MAG-3	Magnetosphere - Mode 3
11	MAG-4	Magnetosphere / Magnetosheath - Mode 1
12	MAG-5	Magnetosheath - Mode 2
13	MAG-C1	Magnetosphere - Data Compression - Mode 1
14	MAG-C2	Magnetosheath - Data Compression - Mode 2
15	CAL	Calibration / Test Mode

Table 3.1. CIS Operational Modes

These 16 modes (Table 3.1) can be grouped into solar wind tracking modes, solar wind study modes with the priority on the upstreaming ions, magnetospheric modes, magnetosheath modes, an RPA mode and a calibration and test mode. These modes correspond to different energy sweeping schemes and different combinations of telemetry products transmitted. On-board calculated moments are always transmitted to the telemetry with a high-time resolution (1 spin). A combination of 2-D and 3-D ion distribution functions, plus other telemetry products, are transmitted in parallel to on-board calculated moments, with a mode-dependent and product-dependent time resolution. Mode change is performed by time-tagged commands, according to the predicted plasma populations anticipated along the Cluster orbit.

Although during the first two years of operations (2001-2002) various CIS mode selection rules have been in use, since 2003 the most commonly used modes are mode 8 (MAG-1) and

13 (MAG-C1) in the magnetosphere, mode 12 (MAG-5) and 14 (MAG-C2) in the magnetosheath, and mode 3 (SW-4) and 5 (SW-C2) in the solar wind. Mode 10 (MAG-3) is also used in the magnetosphere for providing full resolution HIA data at the expense of CODIF data, as e.g. onboard sc1 since the end of 2004, when CODIF failed on this spacecraft (cf. section 3.2). The RPA mode is operated about once per month, either on all spacecraft or on selected spacecraft.

**Magnetospheric Modes (Modes 8 - 11, 13):** They are relatively simple modes, i.e. the full energy-angle ranges are systematically covered. For HIA the different telemetry products (including moments) are deduced from the  $62\text{E} \times 88\Omega$  energy solid angle count rate matrices accumulated on the “high G” section, and eventually reduced to a lower energy resolution by binning together adjacent channels. For CODIF they are deduced from the sensitivity side selected by command and from a similar energy-angle matrix as for HIA and similarly eventually reduced to a lower energy resolution.

**Solar wind tracking modes (Modes 0, 2, 4):** They allow a precise and fast measurement (4 s) of the ion flow parameters ( $\text{H}^+$ ,  $\text{He}^{++}$ ). For that, in the solar wind, for HIA the energy sweep range is automatically reduced when the field-of-view of the “low g” section is facing the  $45^\circ$  sector centred in the solar wind direction. This energy sweep range is adapted every spin, centred on the main solar wind velocity by using a criterion based on the  $\text{H}^+$  thermal and bulk velocities computed during the previous spin (solar wind beam tracking). This allows a higher energy resolution for the solar wind beam data.

**Solar wind / upstreaming ions modes (Modes 1, 3, 5):** In these modes solar wind beam tracking is performed by HIA only once every  $\sim 16$  spins (exact value can vary depending on mode number). During the remaining 15/16 spins a broader energy sweep is used for the solar wind detection by the “low g” section, allowing at the same time the detection of upstreaming ions by the “high G” section, which is then looking in the anti-sunward direction. Detailed 3-D distributions for the solar wind (“low g” section) are then transmitted to the telemetry only during solar wind beam tracking (once every  $\sim 16$  spins), but onboard calculated solar-wind moments are transmitted every spin. Moreover, detailed 3-D distributions from the “high G” section (e.g. for upstreaming ions and/or for interplanetary disturbances) are included in the basic products transmitted to the telemetry.

Outside this  $45^\circ$  sector, the full energy sweep range is used (**solar wind tracking modes and solar wind modes with the priority on the upstreaming ions, i.e. modes 0 - 5**). However, when the field-of-view of the “high G” section is facing the  $45^\circ$  sector centred in the solar wind

direction (cf. Fig. 3.1), the energy sweep stops (and “freezes”) above the solar wind alpha particles energy, to avoid a quick degradation of the MCPs by the intense solar wind beam (modes 0 - 5).

For CODIF, the reduced energy-sweep principle is also used during modes 0 - 5, when the field-of-view of the “high G” section is facing the 45° sector centred in the solar wind direction. Complete energy sweeping is used in the remaining part of the spin (Fig. 3.2).

**Magnetosheath modes (Modes 12, 14)** are like magnetospheric modes. However, starting from 1 November 2003, the energy sweep scheme has been redefined for CODIF. With the new CODIF Magnetosheath Modes (modes 12 and 14), the energy sweeps are truncated and “frozen” at about 2 keV for 16 out of 32 sweeps (when the high-sensitivity side faces the magnetosheath mainstream flow), to save the MCP lifetime.

**Caveat:** The example discussed in section 6.3 illustrates the influence that an inappropriate mode selection can have in the CODIF and HIA data when using HIA low/high G side and/or CODIF low/high G side data in a wrong region (e.g. high G side in the solar wind).

### 3.2 CIS Instrument Status

The overall experiment performance, after about 10 years of operation in space, is good. The particle detection efficiency degradation, due to the MCP gain fatigue mechanism (Prince and Cross, 1971), is moderate for the HIA instrument. For CODIF the efficiency degradation is more pronounced, due to the operational principle of this instrument, requiring the detection of both the ion (“stop” time-of-flight signal) and of the electrons emitted by the carbon foil (“start” time-of-flight signal), plus a “position” signal, to validate the detection of an ion. When processing the raw instrument data to convert them into higher-level data in physical units, these efficiency degradations are compensated by the calibration values used, supplied in the calibration files (cf. Section 4).

The CODIF instrument onboard Cluster **sc1** is switched off since 25 October 2004, due to an MCP high voltage anomaly.

The CIS experiment has been operating nominally on **sc3** until the 11 November 2009 when, during normal operations, it was switched-off by the spacecraft onboard monitoring. Analysis provides evidence for a damaged electronic component, after having operated several times the design lifetime of 2 years and after having received several times the design total radiation dose. The CIS experiment, onboard this spacecraft, is considered as not operational any more.

The HIA instrument is switched off on Cluster **sc4**. On this spacecraft, due to an electrostatic analyser high voltage issue, the HIA energy sweep range is limited between  $\sim 5$  eV/e and  $\sim 400$  eV/e.

The CIS experiment is not operational on Cluster **sc2**.

Table 3.2 gives a summary of the CIS instrument status.

	SC 1	SC 2	SC 3	SC 4
CODIF	Operations until Oct. 2004	Not Operational	One deficient MCP quadrant (cf. section 6.2), until switch-off in Nov. 2009	Normal operations
HIA	Normal operations		Normal operations until Nov. 2009	Switched OFF: reduced energy coverage

Table 3.2. CIS Instrument Status

## 4 Measurement Calibration and Processing procedures

Both CODIF and HIA have been very well calibrated before launch, in vacuum test facilities (Rème et al., 2001). However, due to the in-flight evolution of the MCP detection efficiencies as a function of time, the CIS calibration files are updated regularly. A calibrations catalogue file, which is provided with the calibration files, serves as a pointer to which calibration files to use for each data time period. This catalogue file evolves in an incremental way through the mission, to take into account the existence of new calibration files, which correspond to the instrument particle detection efficiency evolution, or other changes in the instrument. Calibration files include thus parameters that have been determined during ground calibrations in vacuum test facilities and are stable through the mission (e.g. instrument angle response, electrostatic analyser constant used in the calculation of the energy sweep tables, etc.), parameters that change gradually through the mission (e.g. particle detection efficiencies), and parameters that can be changed during the mission by command (e.g. upload of new spin accumulation tables for 3-D ion distributions in the various modes). All of them are equally important in converting raw data into physical units, and are used together.

How the calibration values are used to convert particle raw counts in physical units, such as particle flux, or moments of the ion distribution functions, is described in Appendix 2 of the CAA-CIS Interface Control Document (Dandouras and Barthe, 2007).

A CIS Calibration Report is also provided by the CIS team to the CAA (Dandouras et al., 2009b).

The CIS calibration files are archived at the CAA.

## 5 Key Science Measurements and Datasets

For the archival of the CIS data a multi-level approach has been adopted. The CAA archival includes processed raw data (Level 1 data), moments of the distribution functions (Level 2 data), and calibrated high-resolution data in a variety of physical units (Level 3 data).

Furthermore, the calibration files and high-level processing software are also archived. For details, cf. the CAA-CIS Interface Control Document (Dandouras and Barthe, 2007).

### 5.1 CIS Level 1 Data

CIS Level 1 data are decommutated, decompressed, and time-tagged telemetry data. They are in raw instrument units (no corrections for MCP efficiencies etc.), represent the complete CIS Telemetry, and are the input for all higher-level processing. CIS Level 1 data, together with the CIS calibration files, are in particular the input files for the “cl” software (cf. section 5.6). These data are organised in one file per telemetry product - spacecraft - day, and each file is a time-series of equal-length records. Each data record is complete: time tag, product type, mode info, etc. Data are in IEEE integers or floats.

### 5.2 CIS Level 2 Data: Ion moments

CIS Level 2 data are moments of the particle distribution functions: ion density, velocity, temperature (parallel and perpendicular to the magnetic field components), and pressure. There are two kinds of moments available on the CAA: those produced onboard and those produced on the ground. On-board calculated moments and on ground calculated moments are complementary as the onboard moments have better time resolution while ground moments have better calibration values. The calculations of the moments of the 3-D ion distribution functions are described in Appendix 2 of the CIS-CAA ICD.

The **onboard calculated moments** correspond to the Prime Parameters from the Cluster Science Data System (Daly et al., 2002): on-board calculated moments from the full angular and energy resolution 3-D ion distributions, then reprocessed on ground (total efficiency calibration adjustments, coordinate transformations etc.). However, the FGM CAA data are here used for calculating parallel and perpendicular ion temperatures. In addition, the ion velocity is provided in both GSE and ISR2 reference frame, and the whole pressure tensor is included. On-board calculated moments provide 1-spin time resolution, and are calculated from the full angular and energy resolution 3-D ion distributions.

In addition to the on-board calculated moments, CIS Level 2 data include also CODIF **moments calculated on ground** from the 3-D ion distributions:  $H^+$ ,  $He^+$  and  $O^+$ . These provide better calibration adjustments (per anode efficiency) and are thus more accurate, but have a reduced time and energy resolution.

HIA on ground calculated moments are not supplied, because the same anode calibrations would be used as for the on-board calculated ones, but with a degraded time, energy and angular resolution (no added value).

A software package has also been developed and is available for download at the CAA web site, allowing the user to interactively calculate partial (or total) moments of the ion distributions, for selected energy and solid angle ranges: CODIF (all 4 ion species) and HIA data (cf. section 5.6).

On-board calculated moments and on ground calculated moments from the 3-D ion distributions are thus complementary (cf. section 6.1, data selection guide).

The way moments are calculated from the 3-D ion distribution functions is described in Appendix 2 of the CAA-CIS Interface Control Document.

### ***5.3 CIS Level 3 Data: Ion distribution functions***

CIS Level 3 data are processed high-resolution data: 3-D ion distributions. They are produced by correcting the Level 1 data for detector efficiencies, geometric factors and other information available from the calibration tables, and give measurements in several physical units (in separate files):

- (differential) particle flux (ions  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1}$ )
- particle energy flux (keV  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1}$ )
- particle phase space density (ions  $\text{s}^3 \text{km}^{-6}$ )
- corrected-for-efficiency particle count rate (ions  $\text{s}^{-1}$ )
- raw particle counts (number of ions per counter bin)

These datasets are constructed by joining data of the same ion species from different modes that can have different angular, energy or time resolution, in order to create a single dataset per ion species and per sensitivity type (LS/HS).

**3D ion distribution functions:** The 3-D ion distributions are given in the ISR2 pseudo-GSE reference frame (X sunward, Z is the spacecraft axis and northward pointing). They give the complete  $16 \text{ azimuth} \times 8 \text{ elevation} = 128$  solid angles matrix (by repetition/division), and remove the reduction to a total of 88 solid angles in the telemetry products, where adjacent solid angles near the polar directions have been binned together (for some CIS telemetry products). Solid angles, defined in the distributions, correspond to particle arrival directions (direction of travel of the particle).

**Pitch-angle distribution functions:** In addition to the 3-D distributions, pitch-angle distributions (PADs) are also provided. These are calculated on ground from the 3-D distributions and the magnetic field direction (spacecraft reference frame), are given in particle flux units as a function of the particle energy and pitch-angle (2-D distributions), and their resolution is in 16 angular sectors covering the pitch angle range from  $0^\circ$  to  $180^\circ$ .

**Omni-directional distribution functions:** Omni-directional fluxes (1-D ion distributions as a function of energy, in particle energy flux units) constitute another CIS archived dataset, which provides an overview of the plasma environment.

**Ancillary data:** Besides these 1-D, 2-D and 3-D distributions, some uncalibrated CODIF data sets are also included in the CIS Level 3 data: files with on-board selected ion detection events, MCP monitor rates, and low-angular resolution distributions in  $64 \text{ m/q}$  ranges. These data sets are useful for monitoring instrument performance against eventual background and ion mass species separation, or for searching for minority ion species.

Level 3 archival files are labelled with metadata, i.e. information that describes the dataset and its contents, so as to be easily understandable by the CAA user. These metadata follow the specifications given in the Cluster Metadata Dictionary (Harvey et al., 2008), which has been produced for the CAA project by the CAA Metadata Working Group and the CDPP, the French Plasma Physics Data Centre (<http://cdpp.cesr.fr/>).

## 5.4 CIS Graphical Data Products

The CIS graphical data archived are 6-hour energy-time ion spectrograms. They are pre-formatted displays: PNG graphic files embedded in HTML pages, and they are given at two levels of resolution: browsing and detailed. These spectrograms are supplied separately for

each spacecraft. They are also available at

<http://cluster.cesr.fr:8000/public/spectro/index.php?vue=SCI>.

## 5.5 CIS Calibration Files

CIS calibration files are ASCII files, self-documented (including comments), machine-readable and human-readable. Cf. section 4 about CIS calibrations, and Dandouras et al., 2009b.

At the time of this writing (April 2011) the CODIF calibrations are covering the period up to 2008-01-03 and the HIA calibrations are covering the period up to 2007-10-01. Work is in progress for the following data periods.

## 5.6 CIS Data Processing Software

The CIS data processing software to be archived is composed of two packages:

- The *CIS\_3D\_MOM* software, specially developed for the CAA, allows the user to read the CIS Level 3 files, available at the CAA, and interactively calculate partial or total moments of the ion distributions, for selected energy and solid angle ranges. The input is 3-D ion distribution functions, in CEF-2 format and in corrected-for-efficiency particle count rate units, and the output is ion density, bulk velocity, pressure tensor and temperature, also in CEF-2 format and in the ISR2 pseudo-GSE reference frame. It is written in C and it can be used for either CODIF or HIA data.
- The *cl* software, written in IDL, and developed initially for the CIS team. It reads Level 1 CIS data and calibration files; is interactive, and can generate a large variety of high-resolution graphics (spectrograms, distribution functions, PADs ...) in several physical units. It can also export the results as ASCII (CEF) data files. In addition to the CIS data, this software can also read generic CDF and CEF data files, for correlation studies. For the *cl* software, the user can contact [Emmanuel.Penou@cesr.fr](mailto:Emmanuel.Penou@cesr.fr).

These software packages are available “as documents”, for installation and execution on the end user’s machine.

## 5.7 CIS Data Caveats

An internal caveats database, containing instruments caveats for the whole mission, is available at <http://cluster.cesr.fr:8000/index.php?page=caveats&langue=en>. This database has been also delivered to the CAA.

The caveats are automatically delivered together with the requested datasets to the user if there are caveats for the requested time interval.

Cf. section 6.2 of this document for the main CIS data caveats.

### ***5.8 CIS Data Quality Indexes***

New dataset, under preparation:

Quality indexes for 3 datasets categories (CODIF ground calculated moments and HIA onboard moments, CODIF and HIA PADs, CODIF and HIA 3D datasets) will be delivered, in separate files.

## 6 Recommendations

### 6.1 CIS Data Selection Guide

The following table provides a CIS data selection guide for the CAA user: which CIS datasets are the most suitable, depending on the region and the ion population analysed.

- “1<sup>st</sup> priority” indicates the most suitable datasets. Following priorities indicate data that can be used if the “1<sup>st</sup> priority” data are not available (e.g. mode not selected, instrument OFF etc.), but can be less accurate, as explained in the caveats.
- Text in **gray** indicates partial moments data that the user can calculate for the ion population under study, e.g. calculating the density and the velocity of an ion beam propagating within a denser ambient plasma. This requires running the partial moments software by the user (cf. Section 5.6).

Region or ionic plasma population	Ion moments	Ion distribution functions
Solar wind (solar wind beam)	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: HIA / SW modes / onboard calculated moments</li> <li>2<sup>nd</sup> priority: CODIF / LS side / SW modes / ground calculated moments</li> <li>3<sup>rd</sup> priority: HIA / MAG modes / onboard calculated moments (partial saturation)</li> <li>4<sup>th</sup> priority: CODIF / LS side / MAG modes / ground calculated moments (interference from the HS side)</li> </ul>	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: HIA / LS side / SW modes</li> <li>2<sup>nd</sup> priority: CODIF / LS side / SW modes</li> <li>3<sup>rd</sup> priority: HIA / HS side / MAG modes (partial saturation)</li> <li>4<sup>th</sup> priority: CODIF / LS side / MAG modes (interference from the HS side)</li> </ul>
Solar wind foreshock region : upstreaming ions	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: HIA / HS side / SW or MAG modes / partial moments</li> <li>2<sup>nd</sup> priority: CODIF / HS side / SW modes / partial moments</li> <li>3<sup>rd</sup> priority: CODIF / HS side / MAG modes / partial moments (interference from the solar wind)</li> </ul> <p>Note: these can be obtained only by running the partial moments software (cf. 5.6)</p>	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: HIA / HS side / SW or MAG modes</li> <li>2<sup>nd</sup> priority: CODIF / HS side / SW modes</li> <li>3<sup>rd</sup> priority: CODIF / HS side / MAG modes (interference from the solar wind)</li> </ul>

Magnetosheath	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: HIA / MAG modes / onboard calculated moments</li> <li>2<sup>nd</sup> priority: CODIF / LS side / MAG or MSH modes / ground calculated moments</li> </ul>	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: HIA / HS side / MAG modes</li> <li>2<sup>nd</sup> priority: CODIF / LS side / MAG or MSH modes</li> </ul>
Cusp	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: HIA / MAG modes / onboard calculated moments</li> <li>2<sup>nd</sup> priority: CODIF / LS or HS side / MAG modes / ground calculated moments</li> </ul>	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: HIA / HS side / MAG modes</li> <li>2<sup>nd</sup> priority: CODIF / LS or HS side / MAG modes</li> </ul>

Outer Magnetosphere (including plasma sheet)	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: CODIF / HS side / MAG modes / ground calculated moments</li> <li>2<sup>nd</sup> priority: HIA / MAG modes / onboard calculated moments (can miss higher energy particles)</li> </ul>	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: CODIF / HS side / MAG modes</li> <li>2<sup>nd</sup> priority: HIA / HS side / MAG modes (can miss higher energy particles)</li> </ul>
Magnetosphere: ion beams (e.g. PSBL)	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: CODIF / HS side / MAG modes / partial moments</li> <li>2<sup>nd</sup> priority: HIA / MAG modes / partial moments</li> </ul>	<ul style="list-style-type: none"> <li>1<sup>st</sup> priority: CODIF / HS side / MAG modes</li> <li>2<sup>nd</sup> priority: HIA / HS side / MAG modes</li> </ul>
Inner Magnetosphere: Ring Current population	<ul style="list-style-type: none"> <li>CODIF / HS side / MAG modes / ground calculated moments</li> </ul>	<ul style="list-style-type: none"> <li>CODIF / HS side / MAG Modes</li> </ul>
Inner Magnetosphere: Plasmasheric population	<ul style="list-style-type: none"> <li>CODIF / RPA Mode / partial moments</li> </ul>	<ul style="list-style-type: none"> <li>CODIF / RPA Mode</li> </ul>

HS : High-sensitivity instrument side

LS : Low-sensitivity instrument side

SW modes : Solar wind modes

MAG modes : Magnetospheric modes

MSH modes : Magnetosheath modes

RPA mode : Retarding Potential Analyser mode

## 6.2 CIS Data Caveats

Given the complexity of an ion spectrometer, and the variety of its operational modes, each one being optimised for a different plasma region or measurement objective, consultation of the data caveats by the end user will always be a necessary step in the data analysis (independently of the data level). In addition to the CAA, the CIS caveats are also available at the CIS home page, at <http://cluster.cesr.fr:8000/index.php?page=caveats&langue=en>. Following are some of the most important caveats, which the user of the CIS data should be aware of:

### Only partial moments measured

- **Limited energy range:** The calculated density values are in reality ion partial density values in the energy domain covered by the instrument, typically 25 eV/e to 40 keV/e for CODIF and 5 eV/e to 32 keV/e for HIA. In the presence of cold plasma at energies below the instrument energy threshold, or of hot plasma at energies above the instrument upper energy limit, this partial density is evidently lower than the total plasma density. In the presence of hot plasma at energies above the instrument upper energy limit the result is also underestimated ion bulk velocity, temperature and pressure values.
- **Spacecraft potential:** The instrument energy domain is always defined with respect to the spacecraft potential. Spacecraft charging to a positive floating potential, as can be the case in low density plasmas when the ASPOC ion emitter for spacecraft potential control is not operating (Torkar et al., 2001), repels the low-energy ions which in these cases cannot be detected by CIS (cf. for example section 6.10 of Rème et al., 2001, and section 3.4 of Dandouras et al., 2005). This effect results in a further increase of the difference between the partial density, measured by CIS, and the total plasma density.

### Limitations related to sampling of ion distributions

- **Limited energy/angular resolution:** In addition to the finite energy range, the accuracy of the computed moments is also affected by the finite energy and angular resolution of the two instruments. This is in particular the case for narrow-energy distributions (cold plasmas or cold beams), and/or narrow solid angle beams. CODIF is more sensitive to this effect, due to its coarser energy and angular resolution.

- **Poor counting statistics:** Adequate counting statistics are essential for reliable results. For density calculations, in the case of isotropic plasma distributions, HIA “hits” a lower limit density value of the order of  $0.01 - 0.02 \text{ cm}^{-3}$ . CODIF continues to supply density values down to about  $0.001 - 0.002 \text{ cm}^{-3}$ , although with very poor counting statistics in these cases, which do not allow a reliable calculation of the higher-order moments (velocity, temperature and pressure).
- **Solar wind modes:** The entire velocity phase space, corresponding to the instrument energy domain, is not covered during all modes (cf. section 3.1 and for an example cf. the spectrogram discussed in section 6.3). This is the case during solar wind modes, and during some magnetosheath modes (CODIF data acquired after 1 November 2003 during modes 12 and 14). The result is:
  - Incorrect HIA moment values in the magnetosheath when the instrument is in a solar wind mode (modes 0-5).
  - Incorrect CODIF moment values when data come from the high-sensitivity side and the instrument is in a solar wind mode (modes 0-5).
  - Incorrect CODIF moment values when data come from the high-sensitivity side and the instrument is in mode 12 or 14, for data acquired after 1 November 2003.
- **Eclipses:** During short eclipses the absence of a Sun reference pulse completely desynchronises the HIA data, which become useless, whereas the CODIF data are acquired using an extrapolated Sun reference pulse, and are thus still usable, but with a degraded azimuth accuracy. During long eclipses CIS is off.

### Errors due to onboard data compression and incomplete data transmission

- In order to transmit the full 3D distribution, while overcoming the telemetry rate limitations, a compression algorithm has been introduced, which allows an increased amount of information to be transmitted. This however does not always work well in all situations, and partial data loss can sometimes occur, (partial data gaps).

### Detector saturation, contamination issues

- **Detector saturation:** Ion measurements are sensitive to eventual detector saturation in the presence of high ion fluxes (instrument dead time effects). The most striking example

is the strongly underestimated solar wind density and magnetosheath density by the CODIF high-sensitivity side, while the instrument is operating in a magnetospheric mode (cf. example given in section 6.3). However, these saturation effects are phase space dependent: the detector can be saturated only in a limited energy range and for particles arriving in a given solid angle, where the highest counting rates occur (e.g. solar wind beam), but at the same time can supply reliable measurements in the remaining phase space. Note that HIA data acquired in a magnetospheric mode can also suffer from partial detector saturation when in the solar wind: slightly underestimated densities, by a factor depending on the solar wind density and temperature (Martz et al., 1993).

- **Background noise:** Eventual instrument background counts due to penetrating particles, from the radiation belts around perigee passes or during SEP (Solar Energetic Particles) events, can result in an overestimation of the measured fluxes, and the resulting density values. This effect is stronger for HIA, whereas for CODIF it is mitigated by the time-of-flight technique, which requires both a “start” signal and a “stop” signal, in the correct time-of-flight window, to validate the detection of an ion. However, in the harsh environment of the inner radiation belt, even CODIF suffers from such a background. Figure 6.1 shows an example of background induced on the HIA (top panel) and CODIF (bottom panel) ion counting statistics, due to penetrating particles from the radiation belts, outer and inner.
- **Cross-talk:** CODIF data in the solar wind, if acquired from the low-sensitivity side but with the instrument operating in a magnetospheric mode, can suffer from cross-talk with the high counting rates of the high-sensitivity side, which is then saturated by the solar wind. The result is then overestimated densities and underestimated velocities.
- **Ion species spillover and He<sup>++</sup> contamination:** CODIF mass-separated data can suffer from spillover between neighboring mass channels. He<sup>++</sup> data, in particular, are usually contaminated by H<sup>+</sup> ions, resulting in over-estimated He<sup>++</sup> densities.
- **O<sup>+</sup> contamination:** CODIF O<sup>+</sup> data can be contaminated by penetrating particles in the radiation belts. They can also be slightly contaminated by H<sup>+</sup> ions in very high H<sup>+</sup> flux plasmas, as for example in the magnetosheath. The latter is due to occasionally two uncorrelated H<sup>+</sup> ions, one generating only a “start” time-of-flight signal and the other generating only a “stop” time-of-flight signal, and the time difference between the two being that of an O<sup>+</sup> ion.

- **Ion species effects on HIA:** Presence of ion species other than  $H^+$  in the HIA data results in underestimated densities and in overestimated temperatures and pressures.

### Calibration issues

- **Inter-anode calibration errors :** The  $V_z$  term of the ion bulk velocity is very sensitive to the anode cross-calibrations, and in particular to those of the anodes looking in directions away from the spacecraft spin plane (polar anodes). In some cases the efficiency calibration coefficients cannot completely compensate for strongly asymmetrically decreased efficiencies of such polar anodes, which results in a residual offset of  $V_z$ . This is in particular the case of CODIF onboard Cluster sc3, where one MCP quadrant (southward looking directions on the high-sensitivity side) suffers from a strongly decreased particle detection efficiency. This asymmetric efficiency degradation amplified with time, and for data acquired after 23 February 2003 it cannot anymore be corrected. As a result the  $V_z$  velocity component is highly unreliable (strong offset), and the density suffers from the fact that the instrument under-detects the ions in one hemisphere of the phase space.
- **Detector ageing:** It is accompanied by a degradation of the signal-to-noise ratio (reduced counting statistics).
- **Calibrations accuracy:** Determinations of the evolution of the MCPs detection efficiency are statistical.

### Commanding issues

- **Operation incidents :** They can occasionally result, for short periods, in missing data products, in incorrect MCP high voltage and/or discriminator settings, which reduce the accuracy of the collected data, etc. These are flagged in the caveats for specific data intervals.
- **Data acquired during instrument mode switches:** should be used with caution (+/- up to 2 spins from mode change).

### ***6.3 Example of the influence on the data of an inappropriate mode selection***

The energy-time ion spectrogram, shown in Fig. 6.2, gives an example illustrating the influence that an inappropriate mode selection can have in the CODIF and HIA data, when using HIA low/high G side and/or CODIF low/high G side data in a wrong region.

It includes, from top to bottom, HIA data from the low-sensitivity side (ions in the  $45^\circ \times 45^\circ$  sector centred in the solar wind direction), HIA data from the high-sensitivity side (separately for four azimuthal sectors: ions arriving in the  $90^\circ \times 180^\circ$  sector with a field-of-view pointing in the sun, dusk, tail, and dawn direction respectively), omnidirectional CODIF data for  $H^+$ ,  $He^+$  and  $O^+$  ions respectively, ion velocity components measured by HIA, and ion densities measured by HIA and by CODIF. Instrument operational mode and spacecraft telemetry mode data are also included, as well as spacecraft coordinates. As can be seen in the HIA mode panel, at the top, the instrument was initially in a solar wind - upstreaming ions mode (mode 3). The solar wind narrow-energy beam is clearly identified in the low-sensitivity side HIA spectrogram, while at the same time the high-sensitivity side HIA spectrogram for ions arriving from the sunward looking direction does not detect the solar wind beam. This is due to the energy-sweep scheme adopted during these modes, that stops (and “freezes”) above the solar wind alpha particles energy, as explained in section 3.1. Some high-energy upstreaming ions are however visible at that time, in the high-sensitivity side HIA spectrograms, as well as in the CODIF  $H^+$  spectrogram, which was then operating at the high-sensitivity side. Note that CODIF also does not detect the solar wind beam, for the same reason: the energy-sweep scheme adopted during these modes (cf. Fig. 3.2), but solar wind beam data are supplied by HIA. At 12:40 UT the instrument, while in the solar wind, was switched into mode 12 (magnetosheath mode). Both instruments switched then to an omnidirectional full energy sweep scheme (cf. section 3.1), and the low-sensitivity side of HIA ceased collecting data. The solar wind beam became then detectable in the sunward looking direction spectrogram from the HIA high-sensitivity side (but with a lower energy resolution), and in the CODIF data, collected then from the high-sensitivity instrument side, but with a strong saturation in the solar wind beam energies. Note, however, the ability of the CODIF high-sensitivity side to detect the relatively weak fluxes of the upstreaming ion populations. The energy flux of these upstreaming ions is a factor of  $\sim 2000$  lower than the energy flux of the solar wind beam ions, as this beam population is measured by the low-sensitivity side of HIA. At 14:40 UT the spacecraft entered in the magnetosheath, as revealed



by the broader energy distribution of the detected ions (bow shock heating) and by the anisotropic flow shown in the four directional HIA spectrograms.

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## 8 APPENDIX A: CIS DATASETS

The CIS datasets stored in the CAA are:

Dataset Id	Dataset Title
<b>Ion Moments</b>	
CP_CIS-HIA_ONBOARD_MOMENTS	Ion Moments
CP_CIS-CODIF_HS_H1_MOMENTS	H+ Moments (High sensitivity)
CP_CIS-CODIF_LS_H1_MOMENTS	H+ Moments (Low sensitivity)
CP_CIS-CODIF_HS_He1_MOMENTS	He+ Moments (High sensitivity)
CP_CIS-CODIF_LS_He1_MOMENTS	He+ Moments (Low sensitivity)
CP_CIS-CODIF_HS_O1_MOMENTS	O+ Moments (High sensitivity)
CP_CIS-CODIF_LS_O1_MOMENTS	O+ Moments (Low sensitivity)
<b>Ion 1D omni-directional distributions</b>	
CP_CIS-HIA_HS_1D	Ions 1D distribution (omni-directional, High sensitivity)
CP_CIS-HIA_LS_1D	Ions 1D distribution (omni-directional, Low sensitivity)
CP_CIS-CODIF_H1_1D	H+ 1D distribution (omni-directional)
CP_CIS-CODIF_He1_1D	He+ 1D distribution (omni-directional)
CP_CIS-CODIF_O1_1D	O+ 1D distribution (omni-directional)
<b>Ion 2D pitch angle distributions</b>	
CP_CIS-HIA_PAD_HS_MAG_IONS	Ion pitch angle distribution (High sensitivity)
CP_CIS-CODIF_PAD_HS_H1	H+ pitch angle distribution (High sensitivity)
CP_CIS-CODIF_PAD_LS_H1	H+ pitch angle distribution (Low sensitivity)
CP_CIS-CODIF_PAD_HS_He1	He+ pitch angle distribution (High sensitivity)
CP_CIS-CODIF_PAD_LS_He1	He+ pitch angle distribution (Low sensitivity)
CP_CIS-CODIF_PAD_HS_O1	O+ pitch angle distribution (High sensitivity)
CP_CIS-CODIF_PAD_LS_O1	O+ pitch angle distribution (Low sensitivity)
<b>Ion 3D distributions</b>	
CP_CIS-HIA_HS_MAG_IONS	Ion 3D distribution (High sensitivity, Magnetospheric mode)
CP_CIS-HIA_HS_SW_IONS	Ion 3D distribution (High sensitivity, Solar Wind mode)
CP_CIS-HIA_LS_SW_IONS	Ion 3D distribution (Low sensitivity, Solar Wind mode)
CP_CIS-CODIF_HS_H1	H+ 3D distribution (High sensitivity)
CP_CIS-CODIF_LS_H1	H+ 3D distribution (Low sensitivity)
CP_CIS-CODIF_HS_He2	He++ 3D distribution (High sensitivity)
CP_CIS-CODIF_LS_He2	He++ 3D distribution (Low sensitivity)
CP_CIS-CODIF_HS_He1	He+ 3D distribution (High sensitivity)
CP_CIS-CODIF_LS_He1	He+ 3D distribution (Low sensitivity)
CP_CIS-CODIF_HS_O1	O+ 3D distribution (High sensitivity)
CP_CIS-CODIF_LS_O1	O+ 3D distribution (Low sensitivity)
CP_CIS-CODIF_RPA_H1	H+ 3D distribution (RPA mode)
CP_CIS-CODIF_RPA_He2	He++ 3D distribution (RPA mode)
CP_CIS-CODIF_RPA_He1	He+ 3D distribution (RPA mode)
CP_CIS-CODIF_RPA_O1	O+ 3D distribution (RPA mode)



<b>Ancillary</b>	
CP_CIS-MODES	Instrument modes
CP_CIS-CODIF_CAVEATS	CODIF caveats
CP_CIS-HIA_CAVEATS	HIA caveats
CP_CIS-CODIF_HS_RAT_IONS	Monitor Rates (High sensitivity)
CP_CIS-CODIF_LS_RAT_IONS	Monitor Rates (Low sensitivity)
CP_CIS-CODIF_HS_SEL	Time of Flight selected events (High sensitivity)
CP_CIS-CODIF_LS_SEL	Time of Flight selected events (Low sensitivity)
CP_CIS-CODIF_HS_64M_IONS	Ion 3D distribution, 64 m/q ranges (High sensitivity)
CP_CIS-CODIF_LS_64M_IONS	Ion 3D distribution, 64 m/q ranges (Low sensitivity)
<b>Graphical</b>	
CG_CIS_SPECTRO	Ion spectrograms and moments plots
<b>CSDS Prime and Summary Parameters</b>	
PP_CIS	Preliminary ion parameters (spin resolution)
SP_CIS	Preliminary ion parameters (1 minute resolution)

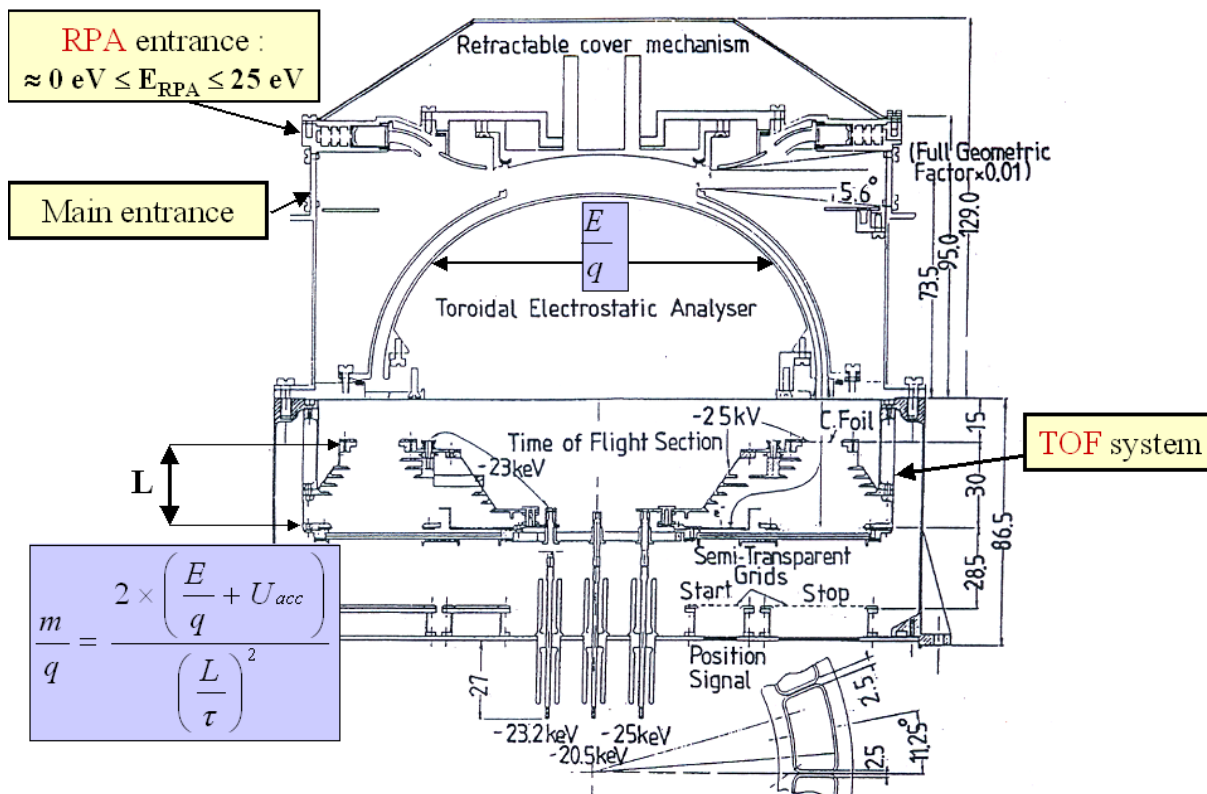


Figure 2.1

Schematic of the CODIF instrument

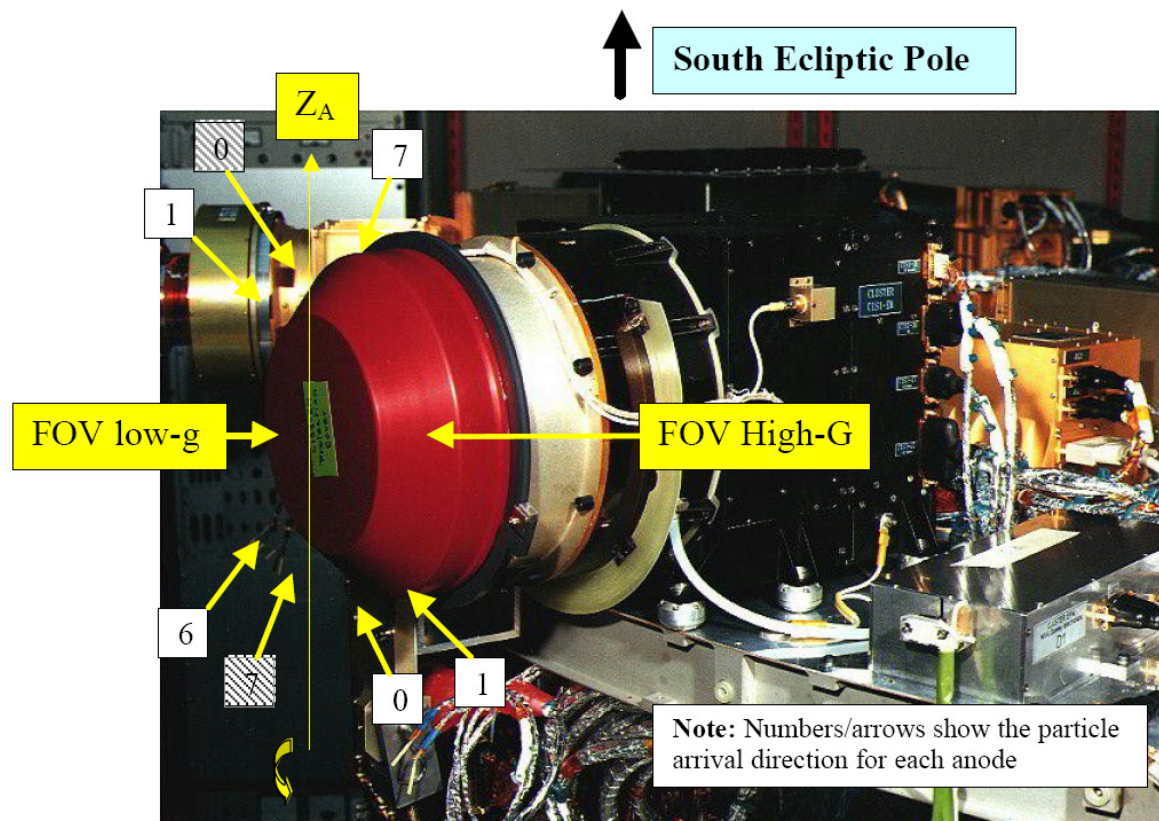


Figure 2.2

*Schematic of the CIS-1 (CODIF) anodes field of view (High-G / low-g), with respect to the main axes.  
In grey are the two "blind" anodes (not used) .*

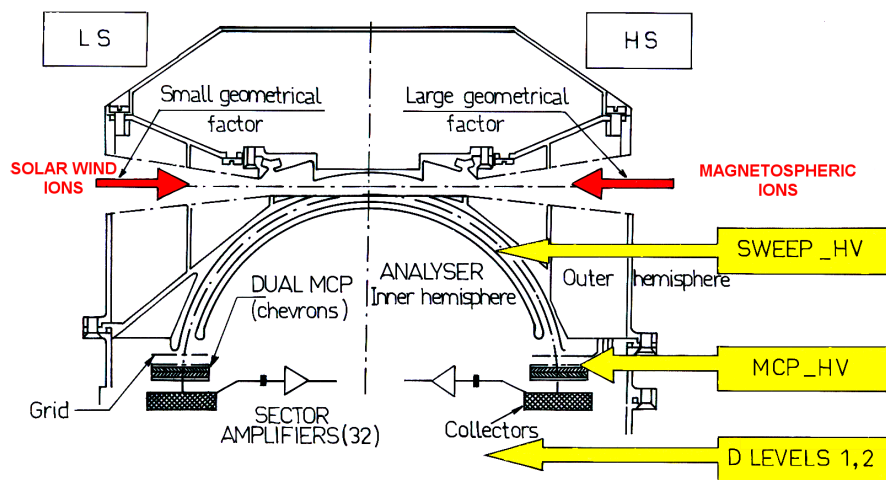


Figure 2.3

Cross sectional view of the HIA instrument.

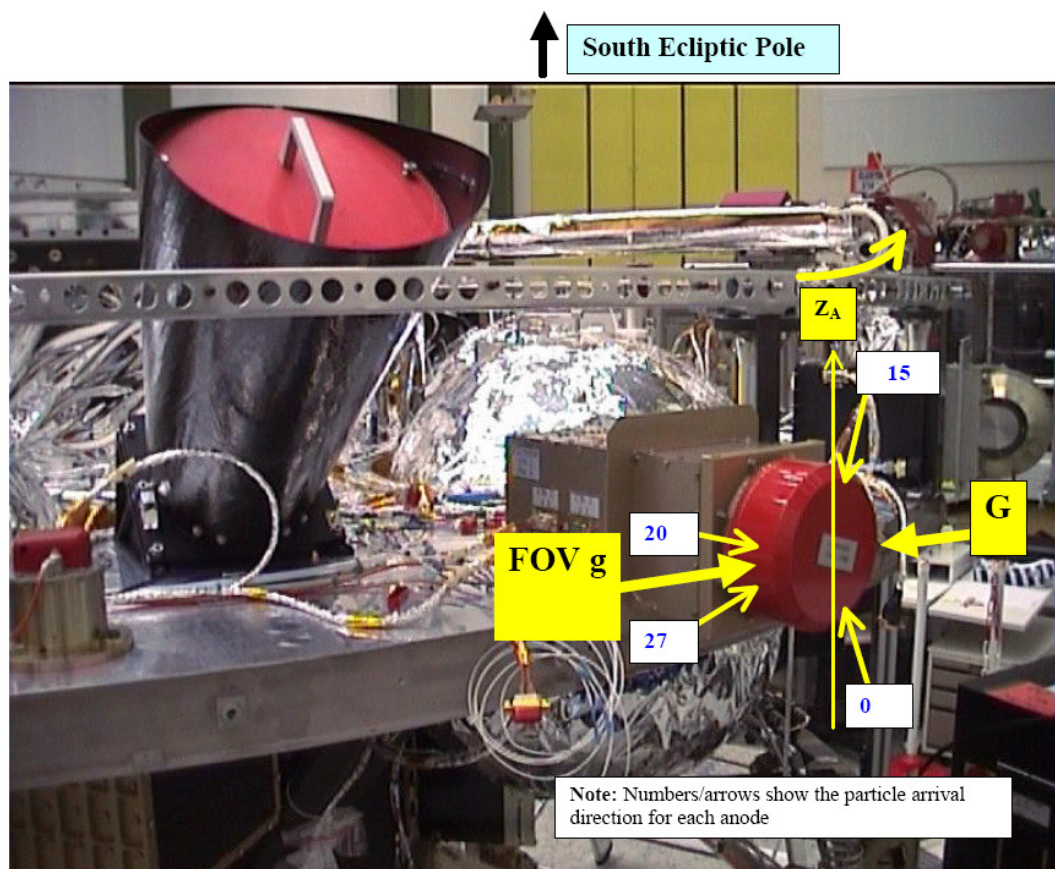


Figure 2.4

*Schematic of the CIS-2 (HIA) anodes field of view (High-G / low-g), with respect to the main axes.*

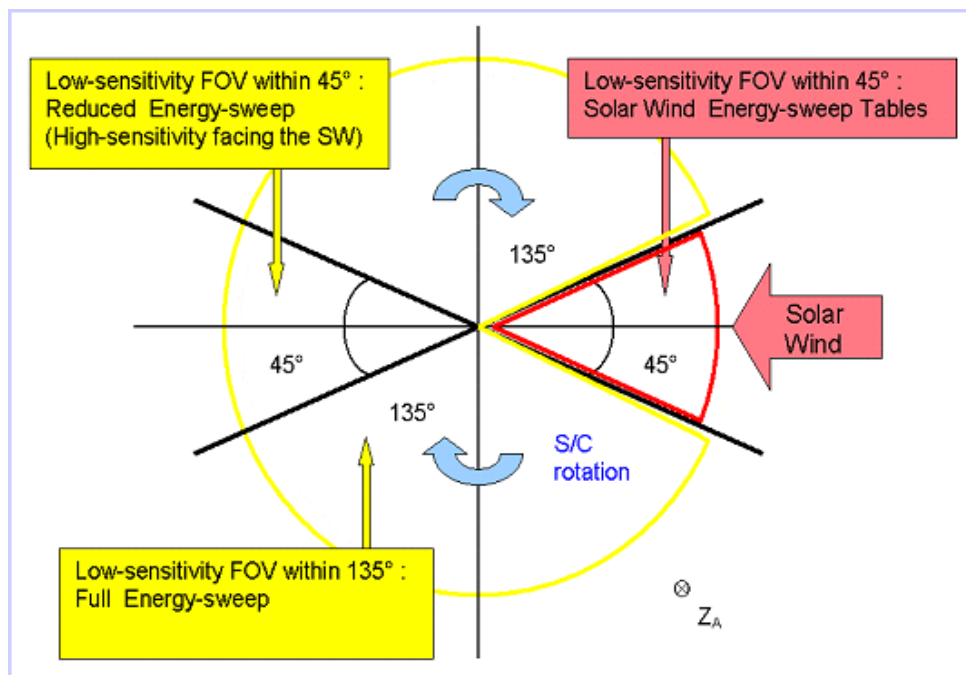


Figure 3.1

*Schematic of the CIS-2 (HIA) energy-sweep scheme, as a function of the instrument field-of-view orientation in the spin plane (solar wind modes 0-5).*

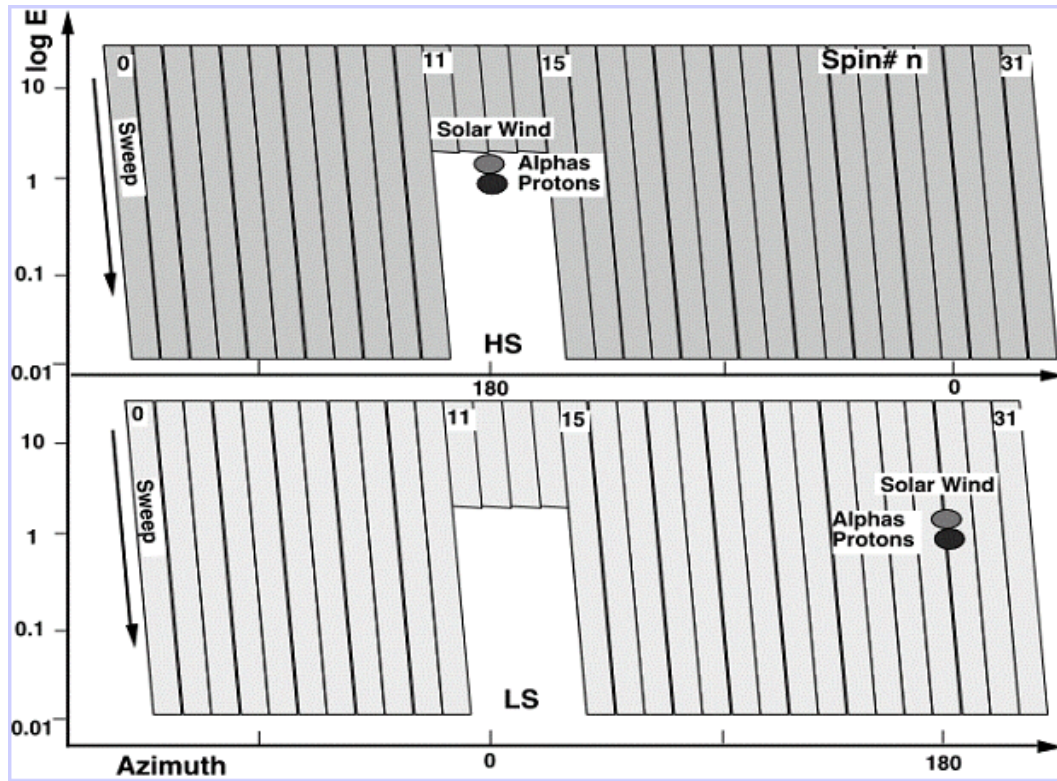


Figure 3.2

Schematic of the CIS-1 (CODIF) energy-sweep scheme, for solar wind modes, as a function of the spin phase: “high G” field-of-view orientation (upper panel,) and “low g” field-of-view orientation (bottom panel). The energy “freeze”, during the reduced energy sweeps, is at about 2 keV.

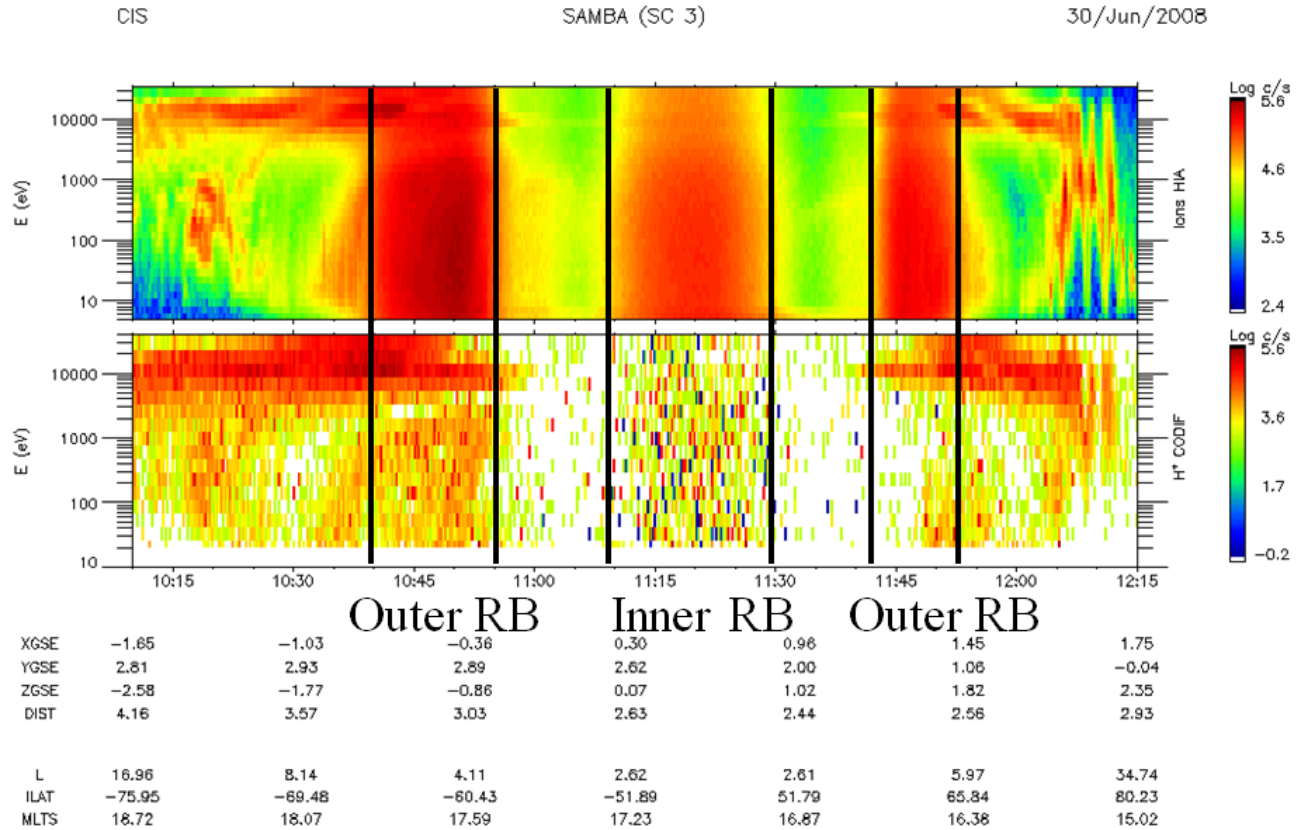
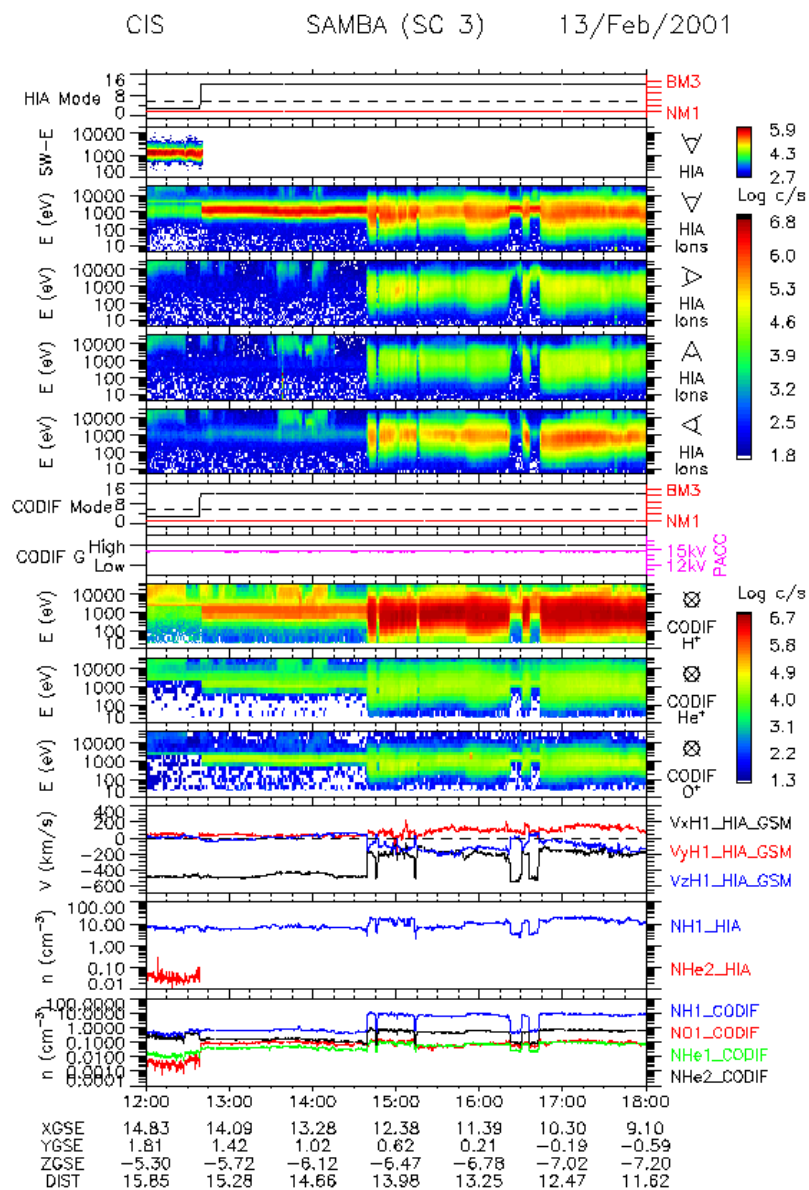


Figure 6.1

Example of background induced on the HIA (top panel) and CODIF (bottom panel) ion counting statistics, due to penetrating particles from the radiation belts.



Produced by CESR. Printing date: 16/Oct/2007 vue\_web\_new.cl

Figure 6.2

CIS energy-time spectrogram, illustrating the influence that can have on the data an inappropriate mode selection. See text for details.